Multi-echo Projection Reconstruction for Real-time Cardiac MRI: Comparison of Echo Trajectories

Dana C. Peters, Richard B. Thompson, Elliot R. McVeigh,
Laboratory of Cardiac Energetics, National Heart, Lung and Blood Institute, Bethesda Maryland, 20892 USA

INTRODUCTION

Multi-echo fast gradient-echo imaging provides high temporal resolution for MRI, useful for free-breathing cardiac imaging [1]. Recently, multi-echo imaging has been investigated using a projection reconstruction (PR) trajectory [2,3]. These techniques have traversed (kr,k?) space using small angular increments between successive echoes (Fig 1a). Choice of k-space trajectory is a determining factor in image quality for multi-echo Cartesian images [4]. Here we investigate the role of k-space trajectories (Fig. 1) for real-time imaging of the heart using multi-echo PR.

Because each projection contains *central* k-space data, phase and amplitude modulations can cause greater artifacts in multi-echo PR, compared to multi-echo Cartesian techniques, where later echoes are dedicated to high spatial frequency collection. However, the projection data itself provides valuable information with which to combine projections, allowing the "resyncing" of the data, for example 0th and 1st order phase correction [3].

Here three k-space trajectories are used for imaging, and the resultant image quality under conditions of off-resonance and echo misalignment are investigated.

METHODS

Acquisition and reconstruction: A 2D multi-phase multi-echo sequence was modified to acquire projections. The pulse sequence (Fig 1c) was implemented on a GE 1.5 T CV/i scanner equipped with 4 G/cm maximum gradient strengths and 150 T/m/s slew rates. The read gradients were modified to traverse angular ray s in k-space, throughout 180?. The three (kr, k?) echo trajectories are shown in Fig. 1a for the case of ETL=4. The echo number for each projection angle is also shown (Fig 1b). For trajectory 1, successive echoes in a shot acquire projections at adjacent angles. For trajectories 2 and 3, the echoes within a shot are at widely spaced angles. Trajectory 2 provides a k-space with sharp discontinuities in echo number at (?=0,180). Trajectory 3 provides k-space which is more smoothly varying in echo number. The echo-spacing is similar for each trajectory. Echo-shifting [5] may be used for trajectories 2 and 3.

Typical scan parameters were: ETL=4,+/-125 kHz, 32 cm FOV, 8 mm slice, 256 to128 radial resolution, 64 Np, full echoes. TR/esp/???? 8-10ms/1.1-1.5ms/15?, cardiac phased-array coil, 120–160 ms temporal window. Reconstruction was performed offline, using a regridding algorithm, or filtered back projection. 1st and 0th order phase correction was investigated.

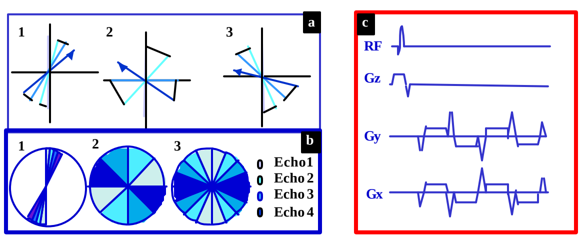
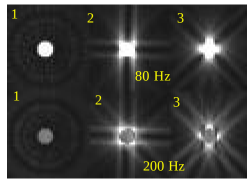


Figure 1a: Three multi-echo k-space trajectories were investigated, shown for ETL=4. Trajectory 1 acquires adjacent projections in successive echoes, trajectories 2 and 3 employ large angular gaps in successive echoes. **Figure 1b**: Each projection is acquired at specific echo in the multi-echo trajectory. The echo number associated with each projection is indicated, for the three trajectories. Note the smooth variation of echo number over k-space for trajectory 3. **Figure 1c:** The multi-echo PR pulse sequence.

RESULTS

Off-resonance Artifact



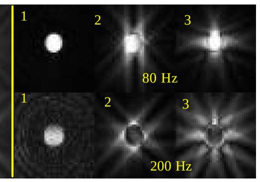


Figure 2: off-resonance **simulations** for the three trajectories, for 80 and 200 Hz

Figure 3: **MR images** acquired off-resonance for the three trajectories, for 80 and 200 Hz

Figures 2 and 3 shows the results of simulations (Fig. 2) and MR imaging (Fig. 3) to investigate off-resonance for the three trajectories. For Fig. 2, a 64 Np acquisition with ETL=4, echo-spacing =1.3 ms, was simulated to image a circular object of radius = 10 pixels in a 256 x 256 grid. The entire object was simulated to be off-resonance by 80 and 200 Hz. Figure 3 shows MR images of tube of water for each of the three trajectories placed off-resonance by 80 and 200 Hz. At 200 Hz, the phase accumulation between echoes is about ?/2, so that signal cancellation occurs. For a single off-resonance object, the images can be fully corrected in post-processing, by 0th order phase correction. However, when regions of an image have different resonant frequencies, such correction is not possible for each frequency.

Echo Alignment and Off-Resonance Artifacts

Is it possible to use the projection data to perform echo-alignment? Echo misalignment is shown in Fig 4a for the three trajectories. Figure 4a displays the multi-echo PR k-space data for each projection angle. Note the different patterns of echo misalignment for the three trajectories. Un-centered k-space echoes appear in image space as a linear phase, 2?k_0, across the projection, which can be estimated [6]:

$$FT\{S(k)\} ? ?(k ? k_0)\} ? f(x)?\exp(i2?k_0x)$$

Uncorrected, they provide artifacts in an image. Figure 4b shows two imaged objects , a water/water object, and a fat/water object. Because fat is an off-resonance object, a linear phase across image space projections appear for some angles. The two objects were imaged with MR using trajectory 1, and ETL=2. Then echo misalignment was estimated as the difference between the linear phase terms for the two echoes in a shot. This difference is plotted in Fig. 4c, both for the water/water object (red dots), and the water/fat object (blue dots). The linear phase difference term of the water/water phantom is due to echo-misalignment, while for the water/fat there are components due to echo misalignment and to off-resonance. We did not attempt to perform echo alignment, because it did not improve the images.

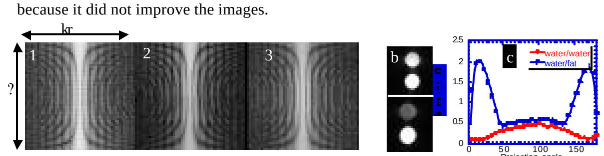


Figure 4: a. k-space sinograms for the three trajectories, showing echo misalignment. b. The phantoms imaged were two tubes containing either (water/water) or (water/fat). c) Echo misalignment is calculated as the difference between the linear phase term of the two echoes in a shot (ETL=2, trajectory=1). Off-resonance objects (i.e. fat/water) contribute additional linear phase term, which is projection angle dependent.

Trajectory 1: Off-resonance maps, and intermediate image reconstruction

Figure 5 shows the results of a 128 Nr, 256 Np multi-echo PR scan, acquired with trajectory 1, with ETL=4, and Esp=1.4ms. The scan was ecg-gated and segmented with VPS=32. A single diastolic frame is shown in 5a. Because trajectory 1 was employed, an undersampled 128 x 64 Np image with can be formed from each echo in the multi-echo readout. These are shown in 5b. It is evident that the image with 256 Np has similar image quality to the 64 Np images. An off-resonance map of the image is shown in Figure 5c, constructed from the phase images from echoes 1 and 3. Potentially, such a map could be used to correct a multi-echo PR image, with trajectory 1.

RESULTS (cont.)

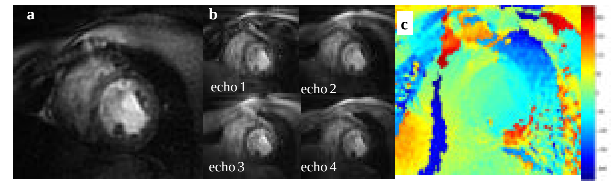


Figure 5: One frame from an ecg-gated multi-echo PR image (trajectory 1), with ETL=4, 128 Nx, 256 Np. Separate images were reconstructed from each of the 4 echoes in the multi-echo readout, using 64 equally spaced projections (Fig 5b). The off-resonance map of the FOV was constructed by subtracting the phase images of echoes 1 and 3. The images from each echo are of similar quality to the image reconstructed from 4 echoes.

Magnitude Back Projection

Figure 6 compares multi-echo PR (4 ETL) phantom images reconstructed with complex and magnitude backprojection. By backprojecting the magnitude of each projection from each echo, a "phaseless" reconstruction is performed. A phantom consisted of tubes of 1) water/water and 2) water/fat (where fat provides off-resonance). The the MPB only performs well if there are no off-resonance objects.

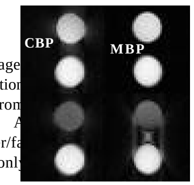


Figure 6: Magnitude back projection compared to complex back projection, for a water/water phantom (top) and water/fat (bottom).

Comparison of Trajectories

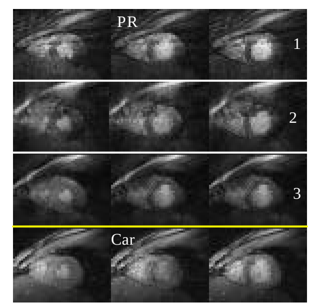


Figure 7: Comparison of the three multi-echo PR trajectories and Cartesian multi-echo trajectory for real-time cardiac imaging. Three consecutive frames are shown. PR: 128 x 64 Np, TR/ ?= 8ms/15?. 4 ETL, +/-125 kHz, esp=1.1 ms, Cartesian (bottom row): 128 x 96 Ny (3/4 nex), TR/?=7ms/15?, esp=0.9ms, 4ETL +/- 125 kHz, "top down" with echo-shifting. Trajectory 3 has the least artifact in this experiment. Echo-shifted PR trajectories did not show clear improvements.

CONCLUSIONS

Multi-echo PR presents the challenge of combining k-space data from projections at different echo times, with each echo providing central k-space information. Trajectory 1 has the greatest resilience to off-resonance (Figs. 2 and 3) and echo misalignment, because the artifacts appear as streaks. Trajectory 3 provided the highest quality real-time cardiac images (Fig. 7). Benefits from "resyncing" the k-space data have not yet been realized in our reconstruction.

REFERENCES

The authors acknowledge the helpful insight provided by J. Andrew Derbyshire.

[1] MB Scheidegger et al., ISMRM 1998, 554.).[2] AC Silva et al., JMR 135 242-247 (1998). [3] V Rasche et al., MRM 42 324-334 (1999). [4] GC Mckinnon, MRM 30 609-616 (1993). [5] DA Feinberg et al., JMR 97,177-183(1992). [6] CB Ahn, IEEE Trans. Med. Imaging, MI-6 32-36(1987).